GREENING OLD INDUSTRIES

Lithium Battery Recycling

The development of lithium-ion batteries ("LIB") for electric vehicles and energy storage systems has led to a clean energy revolution. A challenge posed, however, by the wide spread adoption is ensuring the recycling technology for end-of-life LIB is keeping pace. Hydrometallurgy relies on aqueous solutions to extract materials from the LIB cathode, which includes scarcely available metals including lithium and cobalt. Pyrometallurgy uses heat to convert metal oxides in the battery's raw materials to their metals or other compounds, and Direct Mechanical Recycling works by extracting the cathode materials from the battery for reuse. All three recycling methods, alone or in combination, offer potential solutions, but further advancements are needed from vertically integrated recyclers, independent recyclers, cross-value chain partnerships and regulation policy for the scale-up of sizeable LIB recycling.

INTRODUCTION

Lithium-ion batteries ("LIBs") are at the heart of the clean energy revolution, powering electric vehicles and renewable energy storage systems. Their widespread adoption has, however, led to concerns about the environmental impact of their production, use, and disposal.

CLOSING THE LOOP: THE IMPORTANCE OF A CIRCULAR BATTERY ECONOMY

Chemical companies are developing processes that enable the efficient recovery of valuable materials from used lithium batteries. By reducing the dependence on scarcely available virgin materials, companies can reduce their exposure to insecure supply chains and lessen the damage caused by the mining of these materials.

Recycling is still in its infancy as the current supply of used batteries is insufficient to sustain a profitable recycling business. The American Chemical Society ("ACS") values the current LIB recycling market at $1.7bn. Boston Consulting Group ("BCG") estimates that the revenue potential of a circular LIB economy is set to reach $10bn by 2030, whilst McKinsey expects revenues to grow to $95bn by 2040 (Figure 1).

According to the World Economic Forum ("WEF") and McKinsey, an estimated 54% of end-of life batteries are expected to be recycled by 2030, thereby contributing 7% to the overall demand for raw materials for battery production in that year.

Figure 1. *Forecasted revenues for the LIB recycling market*

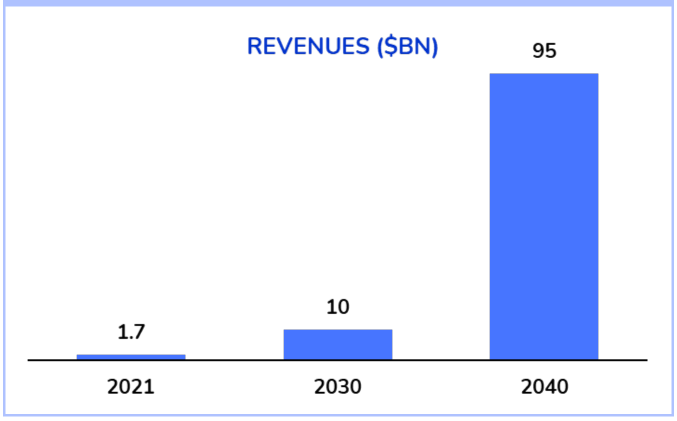
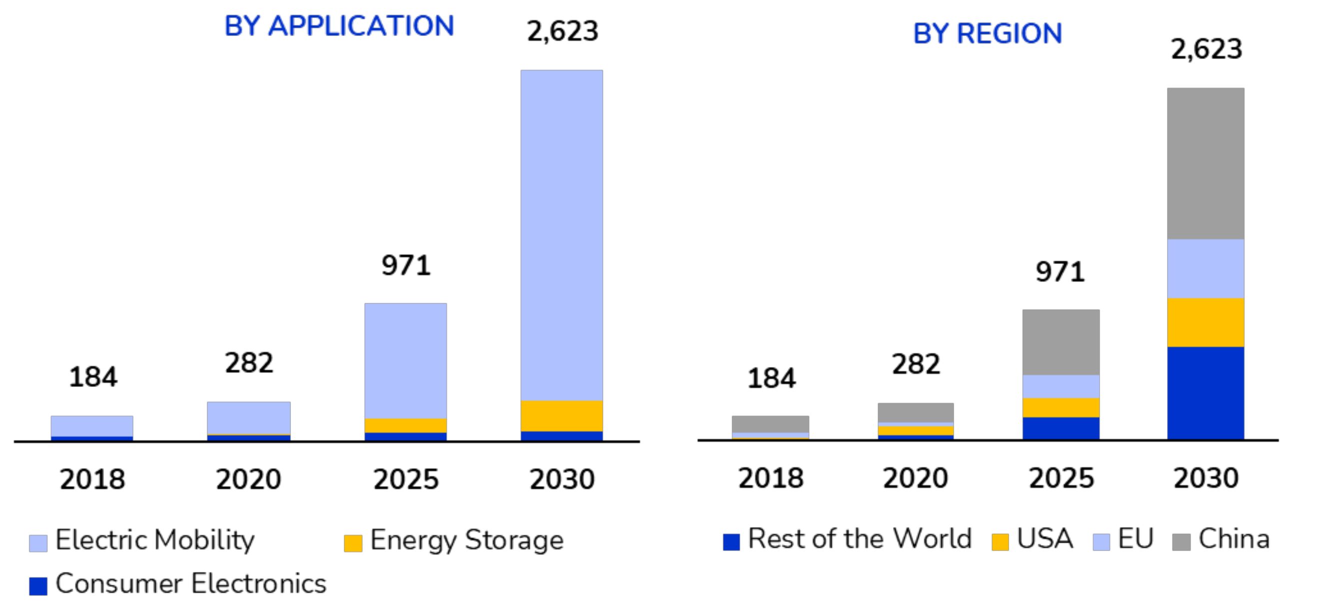


Figure 2. Global Battery Industry Growth by Application and Region by 2030



This will require recycling capacities to be increased by a factor of more than 25 in 2030 compared to today, creating billions of annual revenue along the entire value chain.

The WEF estimates that battery recycling can provide 13% of the global battery demand for cobalt, 5% of nickel and 9% of lithium in 2030. This, however, according to the WEF, is reliant on specific actions from regulators including:

1. Creating "harmonised regulations related to the [cross-border] movement of batteries"
2. Strict recycling targets based on battery material instead of average battery weight
3. Financial incentives

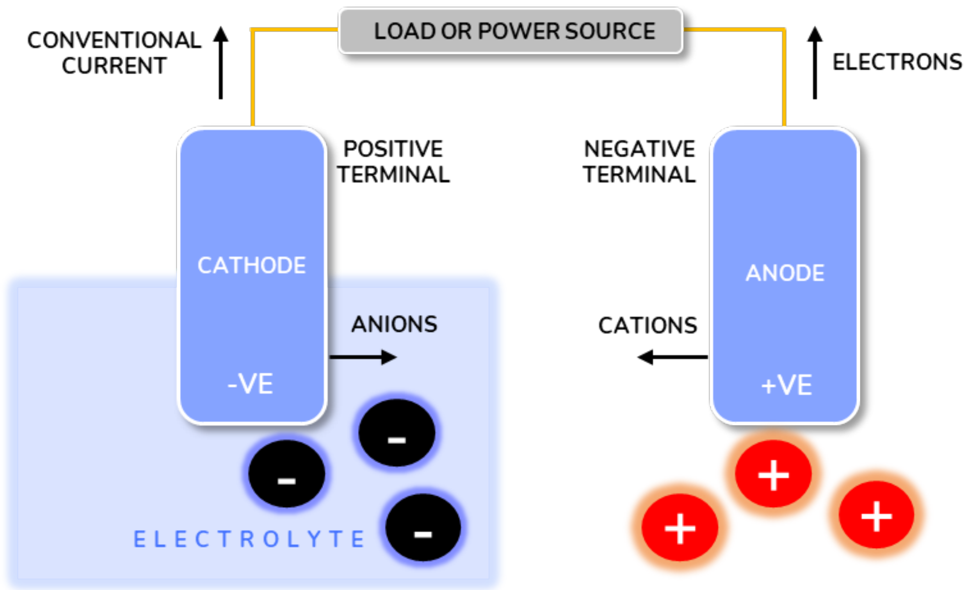
WHAT IS INSIDE A BATTERY?

Before recycling the battery, pre-treatment is necessary. At this stage the batteries are discharged, deactivated, disassembled, and separated.

Following pre-treatment, the batteries are broken into their main components:

- The **cathode** – This is the most important battery component for recycling as it contains scarcely available metals including lithium and cobalt. The recycling and reusing of these metals pose particular political and ethical consequences. Approximately 70% of the world's cobalt is from a single country supplier, and political risk is significant.
- The **anode** – Approximately 95% of material in LIB anodes is based on graphite, either naturally mined or synthetic.
- The **electrolyte** – Most industrial recycling processes ignore recycling the electrolyte. However, the aged organic electrolyte can be removed via calcination or evaporation during pre-treatment steps via a direct sampling method. Sumitomo and Sony in Japan developed a combined pyrometallurgical and hydrometallurgical process, where the plastics and electrolyte parts are directly burnt off during calcination at 1000°C. Metallic parts, such as iron, copper and aluminium can be magnetically separated, whilst active materials like cobalt are recovered via further processing. The lithium salts are recovered with hydrometallurgical treatment. However, these thermal pre-treatment steps release toxic gases during the decomposition of the electrolyte, adding additional complications within the process.

Figure 3. Electrolysis Schematic

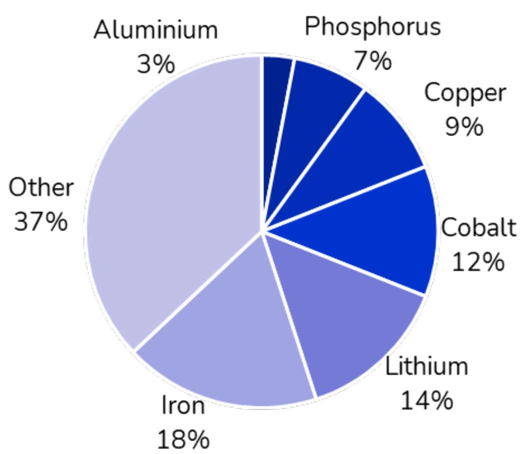


RECOVERABLE COMPONENTS

The weight of a battery depends on its size and energy storage capacity. The larger the battery, the more energy it can store and thus the heavier it will be. Approximately 60-75% of a battery's total weight comes from the cells and the materials they contain. For example, a Tesla Model S has a LIB weighing approximately 544kg with a lithium weight of 62.6kg. The rest of the weight includes cobalt and manganese as well as the battery's metal casing, cabling and thermal management systems.

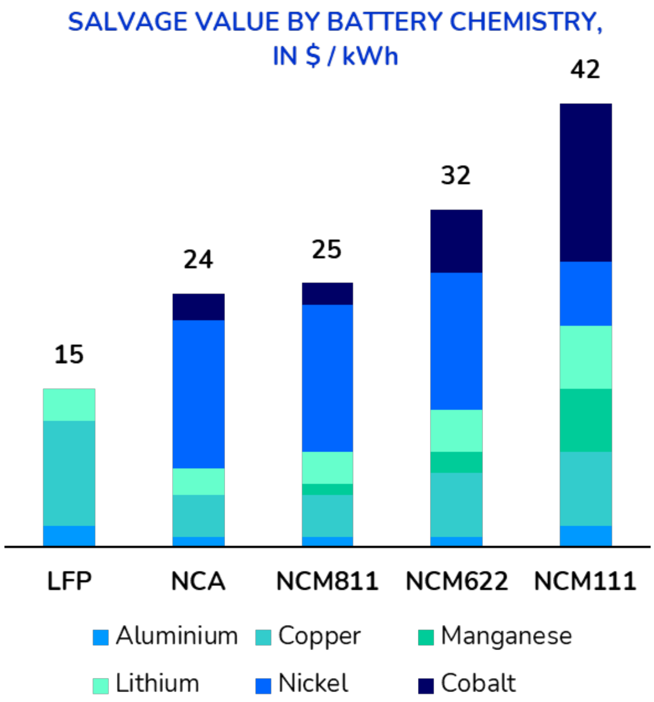
The percentage quantity of the elements that can be extracted from the battery depends on the recycling method. Figure 4 shows the theoretical extraction potential of battery elements in recycled LIBs.

Figure 4. Extractable elements (by %) in recyclable LIBs, per 500,000 tonnes



The salvage value of recycled batteries is also affected by the composition. Different batteries contain different percentage compositions of elements, based on what cell chemistry they employ. For example, as shown in Figure 5 (adapted from BCG), NCM and NCA batteries' salvage values can exceed $25 per kWh.

Figure 5. Value of recycled electric vehicle batteries depending on internal chemistry



"LFP" – lithium-iron-phosphate, "NCA" – nickel-cobalt -aluminium, "NCM" – nickel-cobalt and manganese.

THE BATTERY RECYCLING TECHNOLOGY

Hydrometallurgy relies on aqueous solutions to extract materials from the LIB cathode.

Pyrometallurgy uses heat to convert metal oxides in the battery's raw materials to their metals or other compounds.

Direct recycling works by extracting the cathode materials from the battery for reuse, repurposing or reconditioning.

A combination of hydro- and pyrometallurgy is most widely adopted in recycling LIBs. Both techniques have considerable advantages and disadvantages, as outlined in Table 1.

KEY PLAYERS

There are a number of different business models:

1. Companies make and recycle their own batteries
2. Collaborative companies that are part of the circular economy and operate through partnerships / contracts to close the loop

Vertically integrated recyclers include businesses that offer a holistic coverage of the value chain from logistics to battery recovery. **Umicore**, a leading Belgian recycler of precious metals, relies solely on partnerships to offer closed-loop recycling services to recover battery materials.

ACS estimates Umicore recycles 7,000 tons of batteries per year using both pyrometallurgy and hydrometallurgy. Independent recyclers are mostly startups, including **Li-Cycle**, **Accurec**, **Battery Resourcers**, **Deusenfeld** and **Environstream** who develop new recycling technologies as part of their business model to accommodate environmental regulations and reduce emissions.

Cross-value chain partnerships among recyclers involve specialised companies collaborating to provide end-to-end recycling solutions. Examples include **Veolia** and **Solvay** in Europe and **Heritage Battery Recycling**, **Retriev Technologies**, and **Battery Solutions** in North America. These partnerships bring together different types of expertise to recycle batteries and other materials efficiently.

Automotive OEMs often create partnerships with independent recyclers to integrate a circular economy within their business model. Examples include **Nissan** and chemical giant **Sumitomo** in their joint venture to create 4R Energy. Other OEMs like **Tesla**, **Mercedes** and **VW** introduced internal recycling initiatives. However, partnerships with independent battery recyclers are currently more common as outsourcing models.

POLICY AND REGULATIONS

Currently only a few governments across the globe have introduced regulations for recycling LIBs, however some have shown strong interest in creating globally competitive battery recycling ecosystems.

Whilst the **EU** has no specific regulations governing LIB recycling, a draft regulation for the design, use and recycling of batteries has been proposed. **Germany** on the other hand has designed specific regulations that highlight the responsibilities of LIB manufacturers, consumers and recyclers. These regulations include "The Recycling Law", "Battery Recycling Act" and the "Scrap Automotive Recycling Act".

On a federal level the **USA** has no specific battery recycling regulations, but some states have laws in place requiring recycling services to be offered (see Appendix).

China and **Japan** have well-developed recycling policies. China has numerous laws that regulate the operational standards for battery recycling, including the safety measures, procedures, storage, management, appearance, and specific methods for determining voltage. Some even go as far as specifically applying to LIB recycling. In 2018 China launched the "Work of Power Battery Recycling on New Energy Vehicles" as a pilot plan for battery recycling. Additionally, 2020 saw China pass the "Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution", enacted to control pollution of solid waste including LIBs.

Meanwhile in **Japan**, there is strict regulation for battery recycling, managed by a non-profit organisation. The Japanese government assigns vehicle manufacturers responsibility for their batteries, asking them to maintain up-to-date knowledge of technologies that can be incorporated into their recycling process.

__Table 1.__ LIB Recycling Technologies and Corresponding Advantages and Disadvantages

PROCESS	ADVANTAGES	DISADVANTAGES	CHALLENGES TO BE ADDRESSED	KEY PLAYERS & CORRESPONDING RECYCLING CAPACITY
HYDROMETALLURGY	High recovery rate and product purity Battery components can be more easily recovered Capable of dealing with different battery types simultaneously Less waste gases Low energy consumption	Requires large amounts of water and significant wastewater treatment Pre-treatment methods are labour-intensive Separation methods must be selective to avoid cross-contamination Time consuming	Waste-water treatment Combine pyrometallurgy well	Umicore (7,000 TPA) Glencore (3,000 TPA)
PYROMETALLURGY	Simple operation and short flow (pre-treatment/not needed) Less reagents required compared to hydrometallurgy Capable of dealing with different battery types simultaneously High efficiency	Li is not recovered High energy consumption Low recovery efficiency More waste gases and higher cost of waste gas treatment Limited flexibility in battery feedstock due to fixed investment in facilities	Reduce energy consumption and pollution emissions Reduce toxic gases Combine hydrometallurgy well	Umicore (7,000 TPA) Inmetco (6,000 TPA) Glencore (3,000 TPA)
DIRECT PHYSICAL RECYCLING	Short recovery route High recovery rate Lower energy and reagent costs All components can be recovered More environmentally friendly compared to pyrometallurgy and hydrometallurgy Multiple battery types can be recycled	LIBs must be in good condition for recycling Methods change based on battery composition Larger labour costs Pre-treatment necessary High operational and equipment requirements Increase cost and complexity of facilities to accommodate a range of battery types	Reduced recovery costs Further optimise product performance	

CONCLUSION

In conclusion, establishing a Circular Battery Economy is crucial in addressing the environmental impact of LIBs and in ensuring security of supply of raw materials. Recycling technologies, such as hydrometallurgy, pyrometallurgy and direct recycling, offer potential solutions, but further advancements are needed. Stakeholders, including vertically integrated recyclers, independent recyclers, and cross-value chain partnerships, play key roles in developing sustainable recycling practices. Regulations and policies vary across regions, with China and Japan leading in comprehensive laws, and whilst Europe has a draft proposal, individual countries are further ahead. By embracing a Circular Battery Economy, we can mitigate environmental concerns, improve the supply of critical materials and maximize the value of LIB recycling.

ABOUT NATRIUM CAPITAL

Natrium Capital Limited is an independent Chemicals M&A boutique set up by Alasdair Nisbet in 2012. Natrium Capital provides high level strategic and M&A advice primarily focused on the chemical, personal care, adhesive, engineering materials, paints, inks and coatings, biotechnology and clean technology industries. Headquartered in London, Natrium Capital and team advise on complex global cross-border transactions and have advised on over $100bn transaction value in the sector.

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UNDISCLOSED	€300m	UNDISCLOSED	$360m	$2.1bn
ADVISOR TO	ADVISOR TO	ADVISOR TO	ADVISOR TO	ADVISOR TO
WILBUR-ELLIS	DOMO	SOLVAY	ELEMENTIS	PPG
on the merger of Connell, its Asian Speciality Chemical Distribution business with	in the acquisition of Performance Polyamide Business in Europe from	in the sale of its Amphoteric Surfactant Business in N. America & Europe to	in the acquisition of	in the merger of its chlor-alkali business with Georgia Gulf to form
CALDIC	SOLVAY	OPENGATE CAPITAL	SUMMITREHEIS	axiall

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KEY PLAYERS AND MERGERS & ACQUISITIONS ("M&A")

Companies	HQ	Market Capitalization ($m)	Enterprise Value ($m)	M&A and Important News
UMICORE	*Brussels, Belgium*	*6,684*	*7,943*	Mar'23 – Acquires minority stake in **Blue Current**, the California-based solid-state battery storage firm. Financial details n/d Sep'22 – **VW** and **Umicore** form a JV named **PowerCo**, investing €3bn for precursor and cathode material production in Europe
AMERICAN BATTERY TECHNOLOGY	*Reno, NE*	*526*	*514*	2019 – Sponsored by **BASF**, with access to over $1m wet-lab equip-ment, to develop a full-battery recycling process to extract each indi-
LI CYCLE CORP.	*Toronto, Canada*	*1,006*	*932*	May'22 – Receives $200m investment from **Glencore** to co-develop
REDWOOD MATERIALS	*Carson City, NE*	*N/A*	*N/A*	Jul'21 – Raises > $700m in external funding to develop their battery material recovery process, including tripling the size of their current site facilities
BASF	*Ludwigshafen, Germany*	*43,629*	*64,576*	Jun'22 – Announces commercial scale battery recycling for black mass plant in Schwarzheide, Germany Oct'21 – Forms partnership with **SVOLT** to advance battery recycling solutions
JOHNSON MATTHEY	*London, UK*	*3,830*	*5,143*	May'22 – Agrees to sell Battery Materials BU: **EV Metals Group** ac-quires UK, Poland and German operations, **NanoOne** acquires Canadi-an operations
GLENCORE	*Baar, Switzerland*	*72,218*	*94,881*	**Glencore**, **FCC**, and **Iberdrola** partner to provide lithium-ion battery circularity solutions for Spain and Portugal
GANFENG LITHIUM GROUP	*Jiangxi Province, China*	*16,304*	*17,480*	Jun'22 – Enters into a strategic cooperation with **SVOLT**
ENERSYS	*Reading, PA*	*4,440*	*5,258*	Apr'23 - Acquires **Industrial Battery and Charger Services Limited**
RETRIEV TECHNOLOGIES	*Lancaster, PA*	*N/A*	*N/A*	Mar'22 – Acquires **Wixom**, a US provider of management solutions for end-of-life batteries

GOVERNMENT POLICIES

Country	*Legislation*	*Existing Strategy & Comments*
UK	*Waste batteries and accumulators regulations 2009 (amended 2015)*	○ Waste batteries and accumulators regulations 2009 (amended 2015) ○ Legislation makes it compulsory to collect and recycle batteries and accumulators in order to prevent batteries and accumulators from being incinerated or
EU	*European Union Waste Batteries and Accumulators Directive 2006/66/EC* *EU Battery Regulation (2022)*	○ European Union Waste Batteries and Accumulators Directive 2006/66/EC: Regulations cover 3 battery categories: Automotive, Industrial, Portable ○ Manufacturers must provide access to information on automotive batteries with a capacity of 2 kWh or more to facilitate handling and determine suitability for reuse or recycling ○ Starting from 2027, batteries must be labelled with manufacturer name, battery type, manufacturing date, presence of hazardous substances and other information for recycling or reuse ○ Manufacturers must disclose the quantity of recycled cobalt, lithium, nickel, and lead in new car batteries starting from 2027. The required amount of recycled cobalt and lithium will double by 2035 ○ The EU aims to introduce an electronic battery passport containing comprehensive information for industrial and automotive batteries of 2 kWh or more ○ Battery recycling efficiency > 70% by 2030 ○ Li material recovery rate > 70% by 2030
USA	***Federal*** *The Universal Waste Rule*	○ No specific battery recycling regulations, however used nickel cadmium (Ni-Cd) and small sealed lead acid (Pb) batteries to be managed as Universal Waste (40 CFR Part 273) ○ The Universal Waste Rule prohibits handlers (e.g., contractors) from disposing of waste Ni-Cd and Pb batteries and further indicates that these batteries must
	State	○ On a state level: California, Washington, Minnesota, Florida, Iowa, Vermont, New Jersey, New York, Maine, DC have laws in place in which producers are required to offer or fund battery recycling
CHINA	Work of Power battery recycling on new energy vehicles (2018) Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution (2020)	○ Numerous laws regulate the operational standards for battery recycling (including the safety measures, procedures, storage, management, appearance, methods for determining voltage) sometimes even specific to LIBs ○ In 2018 China launched the "Work of Power battery recycling on new energy vehicles" as a pilot plan for battery recycling ○ In 2020 the "Law of the People's Republic of China on the Prevention and Control of Solid Waste Pollution" was enacted to control pollution of solid waste including LIBs
JAPAN		○ Japan has a non-profit organization (JBRC – Japan Portable Battery Recycling Center) managing battery recycling and special laws regulating it ○ Vehicle manufacturers are assigned responsibility for their batteries and are forced to maintain up-to-date knowledge of battery technologies that can be incorporated into their recycling process